BOUGUER GRAVITY ANOMALY AND ISOSTATIC RESIDUAL GRAVITY MAPS
OF THE WALKER LAKE 1° BY 2° QUADRANGLE, CALIFORNIA AND NEVADA

By

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INTRODUCTION

The accompanying gravity anomaly maps are part of a folio of maps of the Walker Lake 1° by 2° quadrangle, California and Nevada, prepared under the Conterminous United States Mineral Assessment Program. The quadrangle encompasses an area of about 19,500 km^2 along and to the east of the east flank of the Sierra Nevada (fig. 1).

The Bouguer gravity anomaly map of the Walker Lake quadrangle was prepared by interpolating gravity values among 3,447 gravity stations established in the quadrangle and additional stations from adjacent quadrangles. An isostatic residual gravity map was prepared in order to reduce the effect of interfering gravity gradients associated with the isostatic root of the Sierra Nevada. Methods of data reduction and factors that limit the accuracy of the gravity values are discussed in the following sections of this report.

The geologic interpretation of the gravity maps is based on previous studies, sample measurements, and correlation with other maps of the folio including a geologic map (Stewart and others, 1982) and a map showing Mesozoic plutonic rocks (John, 1983). The purpose of the interpretative part of this report is to demonstrate the correlation between gravity anomalies and the mapped geology, to assess the continuation of exposed geologic units beneath the surface, and to suggest the location of concealed subsurface bodies with mineral resource potential. A three-dimensional model of the Little Walker caldera (fig. 6) is used to illustrate a possible quantitative interpretation of a gravity anomaly. A concealed 25-by 75-km Cenozoic batholith along the east flank of the Sierra Nevada with possible lateral extensions is suggested in this report. A possible magmatic mechanism is discussed to augment contemporary explanations for the extensional origin of valleys. The possibility of lower gravity anomalies indicating thinner roof rocks in the basement beneath mountain ranges also is discussed. Furthermore, interpretation of gravity anomalies was applied in discussions with W.D. Menzie (oral commun., 1982) as one of the criteria used to identify and to delineate areas of mineral resource potential.

COMPILATION AND REDUCTION METHODS

The set of gravity data consists of 2,283 stations established by the U.S. Geological Survey and 1,164 stations obtained from other sources (fig. 2). Lists of values and an explanation of methods of data collection and anomaly calculation are in Plouff (1982a). The values of observed gravity were tied to the International Gravity Standardization Network of 1971 (IGSN-71)(Morelli, 1974) by tying the tide-corrected gravity observations to base stations at Hawthorne, Mina, Minden, and Yerington, Nev. (Jablonski, 1974; Defense Mapping Agency, written commun., 1980). Ties among base stations of an auxiliary network within the Walker Lake quadrangle estab-

lished that 14.60 mGal should be subtracted from the observed gravity at stations tied to the California base station network (Chapman, 1966; Robbins and Oliver, 1976) in order to convert to the IGSN-71 datum. Minor adjustments of the observed gravity datums for other previous gravity surveys were determined by multiple gravity values at common stations and extensive repeat measurements during the current study. Minor adjustments of locations or elevations were made for previously established gravity stations, which were mislocated, as indicated on computerized plots, or were compiled before the publication of 7 1/2-minute topographic maps. Redundant stations and stations with doubtful reconciliation of locations with elevations were discarded from the data set. A four-digit code based on location, elevation, and observed gravity (if available) was assigned to the remaining stations, so that the accuracy of calculated gravity anomalies could be individually evaluated.

The source of greatest error in calculating gravity anomalies is the uncertainty of station elevations. The error of the gravity anomaly is 0.2 mGal/m of elevation error. The error is negligible at 1,183 gravity stations that have surveyed elevations or are located near benchmarks. Depending on the methodology used and the topographic contour interval, the error can approach 1.0 mGal for 1,210 gravity stations established near photogrammetrically determined elevations. Elevations were derived from topographic contour interpolation at 694 stations, from altimetry at 127 stations, and from other sources at 111 stations. Unfortunately, most of the published photogrammetrically determined elevations are on hilltops of limited or difficult access. The error of topographic contour interpolation is assumed to be less than or equal to half the contour interval of the map, which corresponds to a 2.4-mGal anomaly error for stations on maps with a contour interval of 24 m (80 ft). As a result of varying barometric conditions in this mountainous area and sparcity of elevation control points, altimetric elevation errors may exceed 10 m, and errors in determining the consequent gravity anomaly may exceed 2.0 mGal.

Conventional circular templates (Hammer, 1939; Swick, 1942) were used to estimate the terrain correction to a distance of 0.9 km for 1,752 stations during the current study and to a distance of 1.28 km for 176 stations by the University of California at Berkeley (M.W. Reynolds, written commun., 1978). Terrain corrections in the remaining distance interval to 166.7 km were determined with a computer program that uses topography digitized with a combination of half-minute, one-minute, and three-minute geographic grids (Plouff, 1977). Terrain corrections for the remaining stations were retained from the original compilations (Robbins and Oliver, 1976; Healey and others, 1980b). The terrain effect of Lake Tahoe, which is about 15 by 35 km and exceeds 400 m in depth, is underestimated by the digital model of surface elevations because the water is treated as rock. Modeling the lake with horizontal layers (Plouff, 1976) shows that the maximum correction in the Walker Lake quad-

rangle is 0.2 mGal at the shore, and the correction decreases to 0.1 mGal beyond 2 km from the shore. The effect of the lake, however, may need to be considered in interpreting gravity anomalies and gradients in adjacent quadrangles. For example, the effect of the water is 1.4 mGal for a station that is 200 m above lake level near the southwest shore, and the effect exceeds 0.5 mGal at the east shore while persisting at the 0.5-mGal level to a station 1,000 m above the lake level 6 km to the east of the shoreline.

Free-air gravity anomalies were determined using the Geodetic Reference System 1967 formula (GRS 67) for the theoretical value of gravity at sea level (International Association of Geodesy, 1971, p. 60) and Swick's (1942, p. 65) formula for the free-air correction. Bouguer, curvature, and terrain corrections at a standard reduction density of 2.67 g/cm^3 were added to the free-air anomaly at each station to determine complete Bouguer gravity anomalies.

The Bouguer gravity anomaly map (sheet 1) was prepared by interpolation of contours among gravity stations within the Walker Lake quadrangle and nearby stations in adjacent quadrangles. The contours closely match those of the Tonopah 1° by 2° quadrangle to the east (Healey and others, 1981), but small offsets reflecting slightly different data sets and interpolation methods occur along the join with the Nevada part of the Mariposa quadrangle to the south (Healey and others, 1980a). The contours do not merge with the adjacent maps to the south and west published by the California Division of Mines and Geology because the datum of observed gravity on those maps is about 14.6 mGal higher than that of the accompanying map, and the International Formula of 1930 (Lambert and Darling, 1931) was used to calculate the theoretical value of gravity at sea level. The net effect is that the level of the Bouguer gravity anomaly on the accompanying map is lower than those of the adjacent California quadrangles by differences ranging from 2.6 mGal along the south edge to 2.9 mGal along the north edge of the quadrangle. The join is exact within the California part of the Walker Lake quadrangle (Oliver and others, 1982) and along the border of the Mariposa quadrangle to the south (Oliver and Robbins, 1982), but the join with the Sacramento quadrangle to the west (Oliver and Robbins, 1974) is somewhat irregular as a result of new stations established during the present study. The join with the Reno quadrangle to the north (Erwin and Berg, 1977) similarly is irregular. The contour level of the accompanying map is 2.0 mGal lower than that of the Reno quadrangle, which adopted the observed-gravity datum of the U.S. National Gravity Base Net (Schwimmer and Rice, 1969) and the International Formula of 1930 (J.W. Erwin, oral commun., 1978).

ISOSTATIC RESIDUAL GRAVITY MAP

Nearly linear, north-northwest-trending gravity contours near the west edge of the Walker Lake quadrangle (sheet 1) reflect major crustal changes and associated density contrasts in the transition zone between the Sierra Nevada batholith and the Basin and Range province to the east. An approximate isostatic anomaly (fig. 3) was subtracted from the Bouguer gravity anomaly at each station to account for the part of the major gradient associated with the mass deficiency of a crustal downwarp (root) into the upper mantle beneath the Sierra Nevada, which isostatically compensates for the excess topographic mass above sea level. The isostatic correction was made by using the computer program of Jachens and Roberts (1981). Parameters assumed for the isostatic model are a normal crustal thickness of 25 km corresponding to stations located along the Pacific coast, a topographic density of 2.67 g/cm^3, and a density contrast of 0.4 g/cm^3 at the base of the crust. Elevations for the ground surface were obtained from the same geo-

graphic 3-minute grid (4.3 km east-west by 5.5 km north-south) used for calculating digital terrain corrections. The digital part of the isostatic correction was carried to a distance of 166.7 km from each station and the remaining correction was interpolated within the program from the worldwide chart of Karki and others (1961). A minor correction was not made for the thinner crust needed beneath Lake Tahoe because water rather than rock is assumed in the topographic model (fig. 4). The net effect would be to slightly lower the values of the isostatic residual gravity shown on sheet 2 near Lake Tahoe.

The magnitude of the isostatic correction is large, but the correction generally is a smoothly varying function of position in the Walker Lake quadrangle (fig. 3). The Bouguer gravity anomalies (sheet 1) range from -264 to -129 mGal with an average of -203±19 mGal, where the latter number is the standard deviation. The residual isostatic gravity (sheet 2) ranges from -61 to +12 mGal with an average of -21±13 mGal, corresponding to an average isostatic correction of 182 mGal. Although the isostatic equilibrium cannot be achieved this simply and the assumed isostatic model undoubtedly differs from more complicated crustal structure obtained by seismic refraction measurements (Eaton, 1966) and corresponding two-dimensional gravity models (Oliver, 1977), the isostatic correction provides a simple method to reduce the interfering effect of gradients associated with deep crustal sources. Lateral density changes within the crust, which depart from the assumed isostatic model, still can be interpreted from the residual isostatic gravity map. Alternate methods of removing interfering regional gravity fields, such as best least-squares fits, wave-number filtering, and upward continuation, are not based on physical models and cannot, for example, distinguish between low gradients associated with density contrasts near the surface and larger contrasts at depth. The mathematical methods generally do not account for varying station elevations, and, hence, could not detect that there is a 2- to 3-mGal difference in anomaly between the stations near Twin Lakes (10 km southwest of Bridgeport, Calif.) and the stations on the surrounding hilltops, which are about 1 km farther from mass deficiency associated with the underlying crustal root. The improvement in the ability to perceive local gravity anomalies associated with near-surface density contrasts, which are partly masked by gravity gradients associated with isostasy, is illustrated by a reduction of the gradient of the Bouguer gravity anomaly from about 100 mGal for 45 km east-northeast from the southwest corner of the quadrangle to 45 mGal in 45 km on the isostatic residual gravity map.

DENSITY MEASUREMENTS

Bulk densities were measured for rock samples collected at 74 sites (sheet 1). The average density of metamorphic rocks of Paleozoic and Mesozoic age collected at 11 sites is 2.74 g/cm^3 with a standard deviation of 0.06 g/cm^3. The average density of plutonic rocks generally of Mesozoic age collected at 37 sites is 2.71±0.07 g/cm^3. The average density of Tertiary volcanic rocks collected at 26 sites is 2.57±0.16 g/cm^3. These measurements supplement densities measured for suites of rocks reported by Oliver (1970; 1977, fig. 3) in the Sierra Nevada and density measurements summarized by Erwin (1970) near Yerington, Nev. D.C. Johannesen (written commun., 1982) measured sample densities associated with geologic mapping of an area in the Wassuk Range 10 to 15 km south of Hawthorne, Nev. He determined an average density of 2.61±0.01 g/cm^3 for 112 samples of granodiorite, 2.63±0.02/cm^3 for 50 samples of granite, 2.57 g/cm^3 for 33 samples of metamorphic rock, and 2.65 g/cm^3 for 31 samples of Tertiary andesite. Armin and John (1983) measured an average density of 2.70±0.04

g/cm^3 for 128 samples of granitic rock collected near Lake Tahoe.

Snyder and Healey (1983) compiled bulk densities from gamma-gamma logs of 14 drill holes located in an area about 150 km east of the Walker Lake quadrangle. They obtained average densities of 2.60 g/cm^3 for granite from one hole, 2.31±0.08 g/cm^3 for unspecified kinds of volcanic rocks from 9 holes, and 2.10±0.13 g/cm^3 for Quaternary alluvium from 10 holes. The density of alluvium measured in place is especially valuable because measurement of densities for hand samples of alluvium is difficult.

DISCUSSION

REGIONAL FEATURES

A strong regional gradient is present on the isostatic residual gravity map along the crest of the Sierra Nevada (sheet 2). This gradient reflects a combination of uncertainty of the parameters related to the assumed simple isostatic model, intracrustal density contrasts along the east edge of the Sierra Nevada batholith, and a possible underlying zone of transition between oceanic rocks and less dense continental rocks along a continental border of Mesozoic age (Oliver, 1977, p. 458). The gradient decreases northeastward to a northwest-trending gravity trough between Mono Lake and Lake Tahoe. Regional gravity values increase northeastward from the gravity trough to the complexly shaped crest of a regional gravity high near Hawthorne, Nev. Cogbill (1979, p. 155) attributed this increase to a combination of a northeastward 5- to 10-km thinning of the crust and a northeastward decrease of underlying granitic plutons, which are less dense than rocks of the surrounding basement.

The gravity trough along the east flank of the Sierra Nevada between Bridgeport and Markleeville, Calif., has a northeast boundary near the Nevada-California state line and forms a 25- by 75-km closed low, which is approximately outlined by the -35-mGal contour. In contrast to the Bridgeport-Markleeville gravity low, other elongate gravity lows spaced irregularly over a distance exceeding 300 km along the east flank of the Sierra Nevada have higher amplitudes, have smoother elliptical boundaries, and overlie sedimentary basins. Those gravity lows usually are interpreted as a reflection of thick underlying wedges of sedimentary deposits in downdropped blocks adjacent to the Sierra Nevada range front (Healy and Press, 1964). Plouff and Isherwood (1980), however, interpreted the southeast lobe of a 30- by 80-km gravity low with prominent peripheral gradients centered at Owens Valley as a possible magma chamber near the Coso Range, Calif. An isostatic residual gravity map (not available at the time of their interpretation) now clarifies the boundary. A small part of the Bridgeport-Markleeville gravity low reflects local thickening of sedimentary deposits in Bridgeport Valley. Tertiary and older rocks are predominant within the rest of the anomaly and extend beneath the apparently satellitic gravity lows outside the -35-mGal contour.

Although anomalies within the large gravity low are complex and the periphery of the Bridgeport-Markleeville low is irregularly shaped, segments of fairly continuous gravity gradients centered between the -35 and -30-mGal contours suggest that the gravity low outlines a large body of relatively low density, possibly with steep edges. The amplitude of the gravity low is about 15 to 20 mGal.

The major gravity low may outline the thickest or shallowest part of an underlying batholith of Cenozoic age from which the Tertiary volcanic rocks at the surface were derived. Geologic evidence for the existence of a Cenozoic batholith at relatively shallow depth includes hot springs and small outcrops of rhyolitic intrusive rocks of Tertiary age within and near the large gravity low (sheet 2; Stewart and others, 1982) and the Little Walker caldera (Noble and others, 1974) near the center of the gravity low. The rocks of the proposed Cenozoic batholith that cause the observed gravity low may be less dense than the surrounding basement and roof rocks for at least five reasons. First, the younger rocks of the batholith, although perhaps of similar composition to the surrounding wallrocks, have been subjected to a shorter time of compression associated with tectonic stress and depth of burial. The contrast in density, however, generally would be insignificant. Second, the batholithic rock may partly consist of glass, which can be 0.2 g/cm^3 less dense than crystalline rock of the same composition (Daly and others, 1966, table 4-3). Glass, however, usually forms near the surface under conditions of rapid cooling and is unlikely to be present at depth in substantial amounts. Third, the upper part of the postulated batholith may have relatively low density as a result of vertical zonation within the magma chamber; that is, more felsic, less dense rock components rose buoyantly toward the top of the magma chamber, and dense components sank as a result of chemical differentiation. A process of thermogravitational diffusion was suggested by Hildreth (1979) to explain zonation in the magma chamber from which the Bishop Tuff was erupted. Fourth, upper levels of the former magma chamber may be depleted of mafic components, which were largely extruded as Tertiary andesite now prevalent at the surface. Fifth, the batholith may still contain substantial amounts of magma. Heat and whatever convective-transfer process, including buoyancy, that caused and distributed the initial melt, however, would need to have been replenished until nearly the present time in order to maintain the liquid state.

No quantitative modeling of the batholith configuration, such as was attempted for a postulated batholith beneath the San Juan Mountains, Colo. (Plouff and Pakiser, 1972), is feasible because of the irregular shape of the anomaly and the unknown contribution of density contrasts associated with major intracrustal changes along the flanks of the Sierra Nevada. Assuming that the upper part of the batholithic rocks are 0.15 g/cm^3 less dense than the surrounding wallrocks, and the amplitude of the anomaly is 15 mGal, the upper part of the batholith has a thickness of 2.4 km.

VALLEYS

Elongated gravity lows with amplitudes ranging from 10 to 20 mGal associated with wedges of Quaternary deposits on the downdropped side of basin-range faults include Carson River, Smith, Mason, Walker Lake, and Soda Springs Valleys. An apparently fault-associated gravity low also overlies Quaternary deposits in Alkali Flat of Gabbs Valley in the northeast corner of the quadrangle. The prominent elongated gravity low in the eastern part of Gabbs Valley overlies Tertiary sedimentary rocks.

The gravity map provides a method to estimate the configuration of the interface between sedimentary deposits and bedrock underlying valleys. Generally, the location of the thickest deposits would coincide with the location of the lowest gravity values. Greater anomaly amplitudes reflect greater thicknesses of sedimentary deposits, and the highest gravity gradients would overlie the steepest flanks of the valley. For example, Erwin (1970) estimated the thickness of fill in Smith and Mason Valleys on the basis of gravity data. A gravity profile of closely spaced stations near Hawthorne, Nev. (fig. 5), reveals the concealed edge of the pediment aligned with the range-front scarp (Dohrenwend, 1982) at the west flank of Walker Lake Valley. The profile also has a change in slope that may overlie an older fault formerly at

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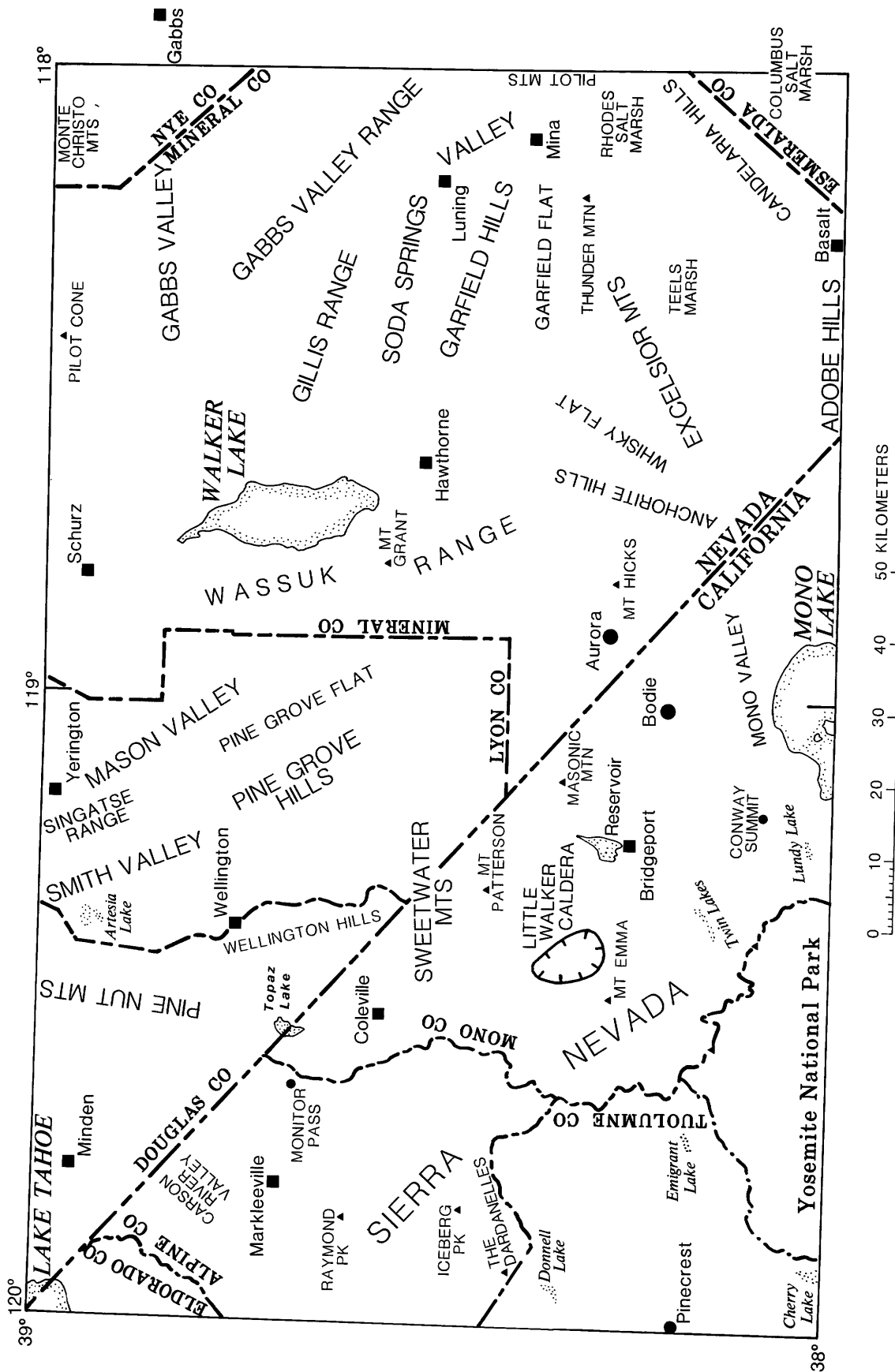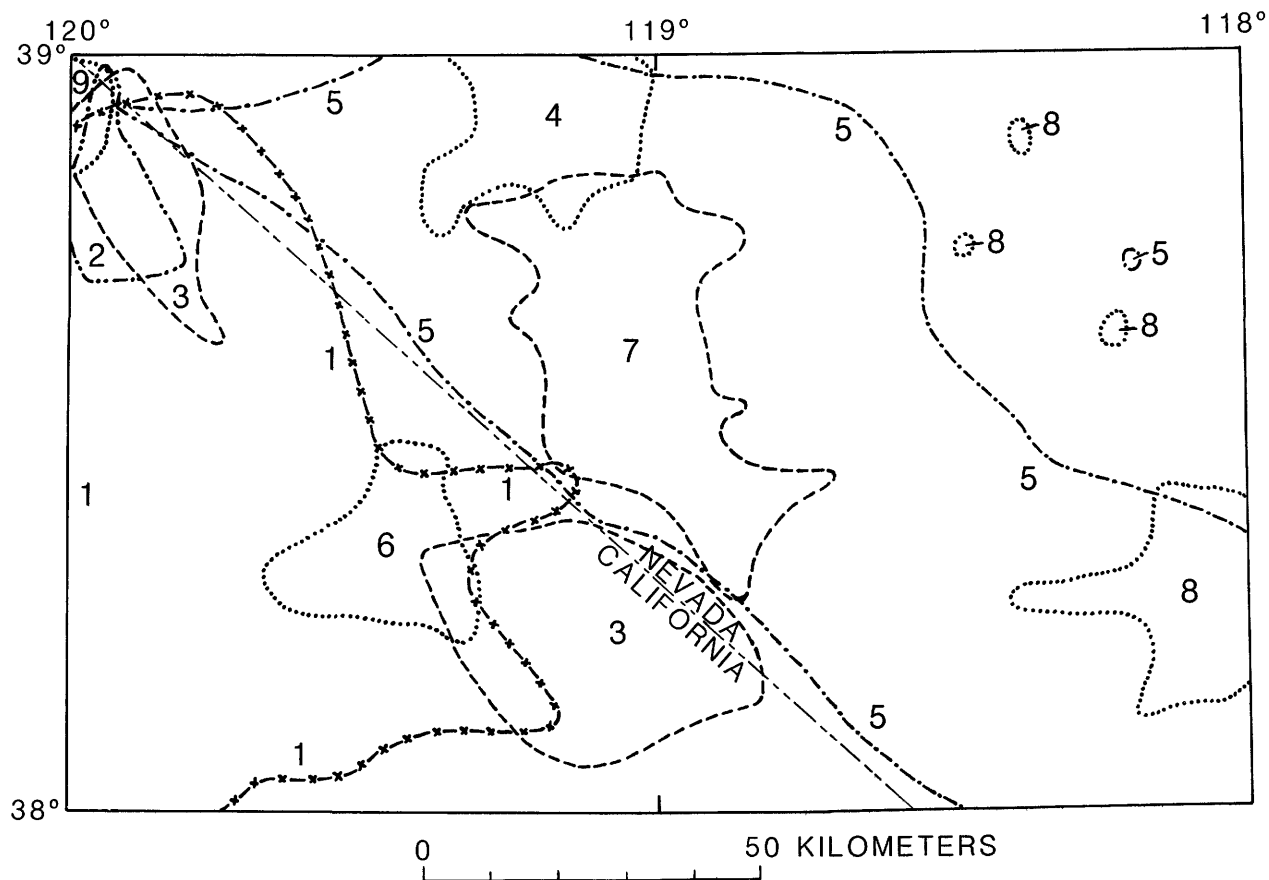
Figure 1.--Index map showing locations discussed in text.

Figure 2.—Locations of gravity data. Data collected by the U.S. Geological
    Survey are distributed throughout quadrangle.

EXPLANATION

A, area in figure; N, number of gravity stations obtained from
contributor

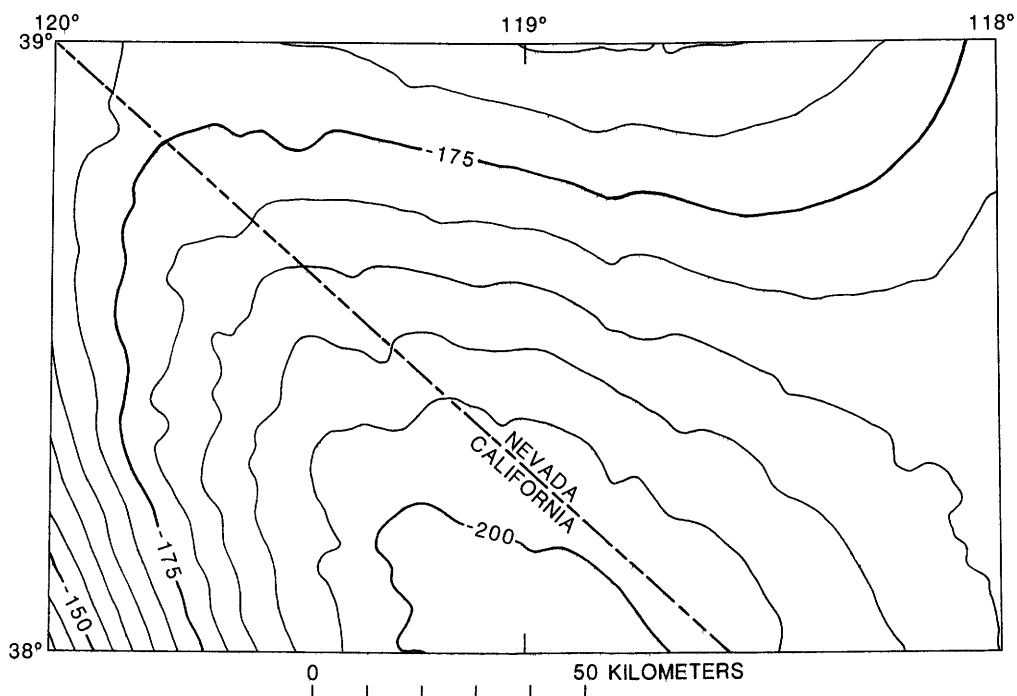| A	N	Contributor
1	34	University of California, Berkeley, Calif., (J.F. Evernden, written commun., 1961; Robbins and Oliver, 1976)
2	9	Jet Propulsion Laboratory, Pasadena, Calif., (A.A. Loomis, written commun., 1967; Robbins and Oliver, 1976)
3	150	California Division of Mines and Geology (Robbins and Oliver, 1976; R.H. Chapman, written commun., 1980)
4	45	Nevada Bureau of Mines and Geology (Erwin, 1970; J.W. Erwin, written commun., 1978)
5	125	Aeronautical Chart and Information Center (written commun., 1978)
6	148	Stanford University, Stanford, Calif., (Oliver, 1974; Oliver and Robbins, 1976)
7	383	University of California, Berkeley, Calif. (C.M. Gilbert and M.W. Reynolds, written commun., 1978)
8	207	Northwestern University (Healey and others, 1980b; A.H. Cogbill, Jr., written commun., 1980)
9	63	Blum (1979)
	2,283	U.S. Geological Survey (Pakiser and others, 1964; Robbins and Oliver, 1976; Healey and others, 1980b; D.K. Maurer, written commun., 1981; Plouff, 1982a) located throughout the quadrangle

Figure 3.--Gravity anomaly of crustal downwarp caused by local isostatic
compensation of the mass above sea level. Contour interval, 5 mGal.

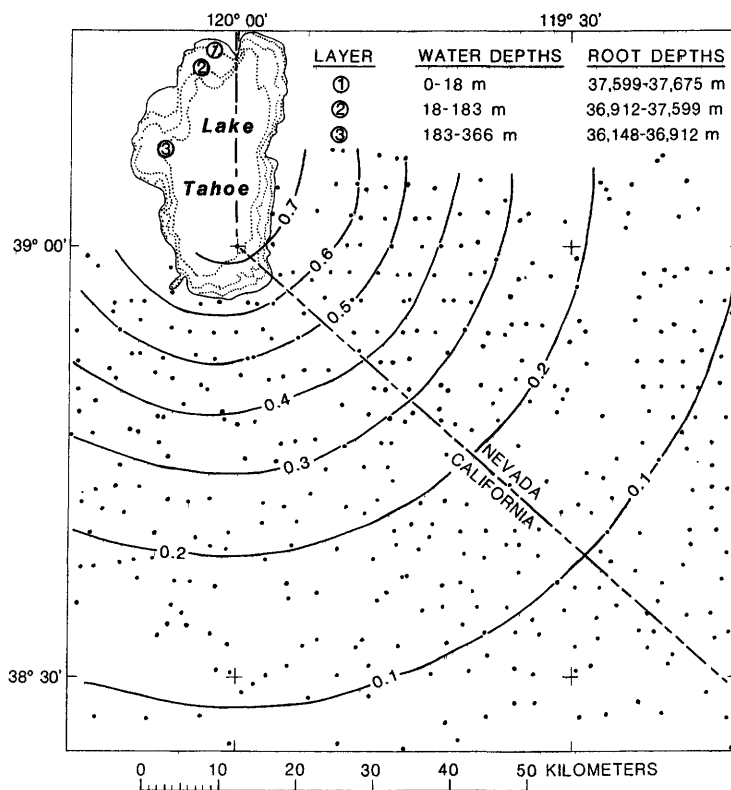| LAYER	WATER DEPTHS	ROOT DEPTHS
①	0-18 m	37,599-37,675 m
②	18-183 m	36,912-37,599 m
③	183-366 m	36,148-36,912 m

Figure 4.--Gravity anomaly to be added to the values of isostatic compensation
(fig. 3) or to be subtracted from the isostatic residual gravity anomaly
(sheet 2) in order to account for the mass of water in Lake Tahoe rather
than rock. Contour interval, 0.1 mGal. Dots indicate gravity stations.
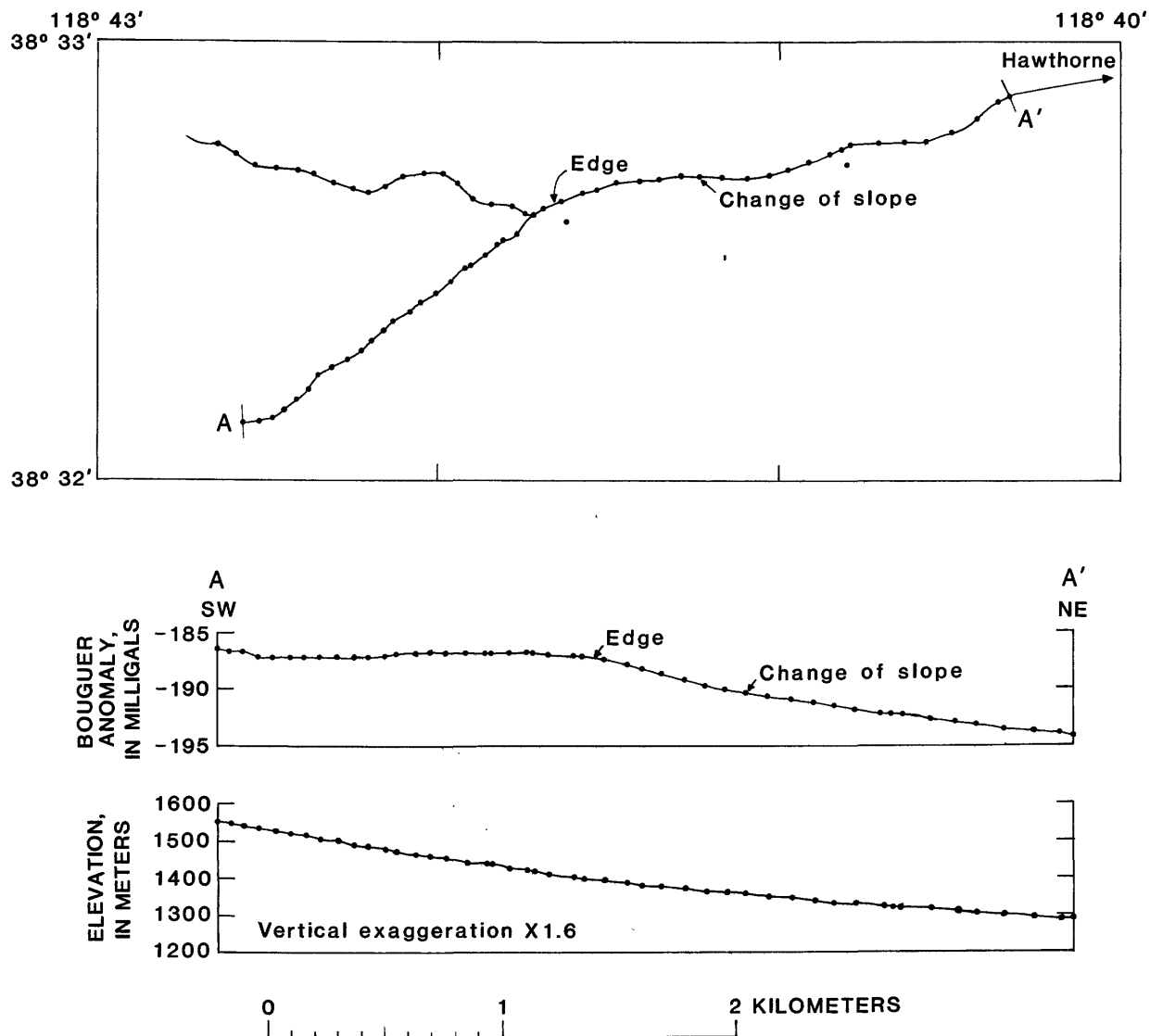Depths of root are relative to sea level.

Figure 5.--Location of gravity stations and gravity profile A-A' near east edge of Wassuk Range. See sheet 1 for location of profile. Dots indicate gravity stations.
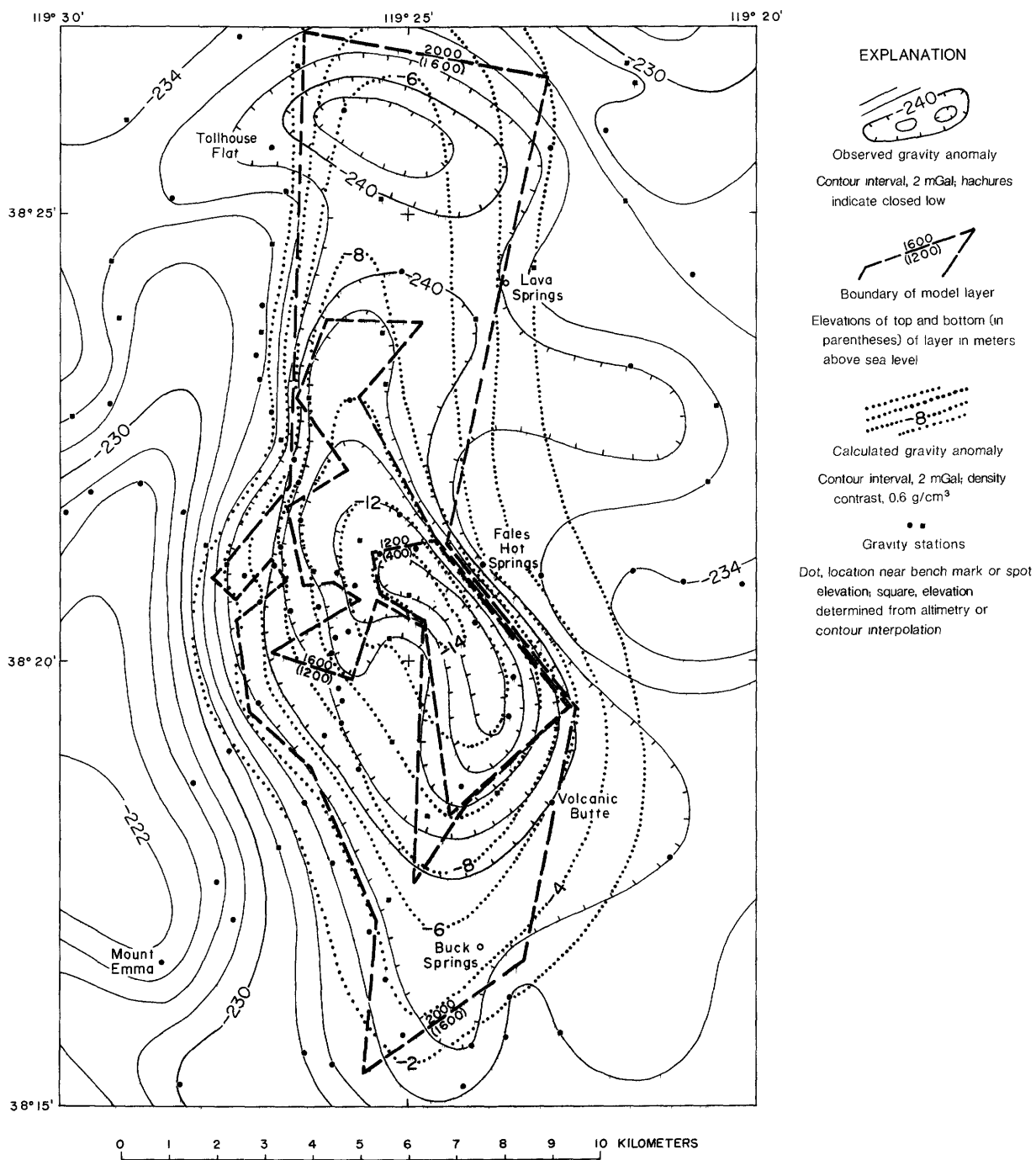
Figure 6.--Gravity model of the Little Walker caldera.

16